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Design and Construction of a Parallel Cyclone System for Kaolin Beneficiation

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Abstract: Kaolin is a very important substance commonly used in many industrial chemical production processes due to its physical properties such as whiteness and brightness in addition to its chemically inert nature. In its raw form, kaolin contains quite a few numbers of different kinds of impurities that must be removed before it is used for production of other chemicals. Kaolin is beneficiated (treated) for removal of impurities capable of distorting its usage in chemical processes. Thus, this article presents the design and construction of a highly efficient parallel air cyclone system with a feeding capacity of 182 kgh^{-1} using Computer Aided Process and Equipment Design (CAPED) Software package. The system was tested and the yield obtained is 30.1%. This result is a significant improvement compare to the average yield of 15% reported in literature for a single state cyclone system. In addition, the parallel cyclone has an average pressure drop of 746.7 Pa and the Particle Size Distribution (PSD) analysis shows that the clay content significantly improves from 46% to an average of 65% after beneficiation. The X-ray Diffraction Analysis (XRD) analysis also showed that the level of beneficiation obtained using the rig improved the kaolinite content in the raw kaolin to an average of 67.8%, the quartz in the feed was reduced to an average of 86.3% while the mica in the feed was reduced by an average of 56.7%.

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INTRODUCTION

Cyclonic separation is a technique of removing particulate impurities from air, gas or liquid stream without the use of filters through vortex separation. Rotational effects and gravity are used to separate mixtures of solids and fluids. A high-speed rotating (air) flow is established within a cylindrical or conical container called a cyclone. The operating mechanism of a cyclone is such that air flows in a helical pattern, beginning at the top (wide end) of the cyclone and ending at the bottom (narrow) end before exiting the cyclone in a straight stream through the center of the cyclone and out through the top. Larger (denser) particles in the rotating stream have too much inertia to follow the tight curve of the stream and strike the outside wall then falling to the bottom of the cyclone where they can be removed. In a conical system as the rotating flow moves towards the narrow end of the cyclone, the rotational radius of the stream is reduced, thus, separating smaller particles (Bashir, 2015). The cyclone geometry, together with flow rate define the cut point of the cyclone. Particles larger than the cut point will be removed with a greater efficiency and smaller particles with a lower efficiency (Xiong *et al*., 2014). Cyclones are widely used because they are easy to construct, inspect and maintain. They are also relatively economical to operate and can be adapted to different operational conditions (Wang and Yu, 2008). There are two types of cyclones; air cyclone and hydro cyclone. Air cyclones are the most common types of gas-solid separation devices used in diverse industrial processes (Ramachandran and Sivakumar, 2015). The primary challenge faced by a single stage air cyclone system is the relatively low collection efficiency for particle below 15 μm (Zhao and Su, 2010). However, recycling of under-flow and application of multistage cyclone system can lead to improvement in the efficiency. Kaolin is available in commercial quantity in Nigeria and it has not been put to optimum use due to unavailable of equipment to beneficiate it. Kaolin are exploited for a wide range of industrial applications such as the production of paper, ceramics (for increasing strength, abrasion resistance and rigidity), plastics (as a filler) and paint (as a filler and thickening agent). Therefore, so, it has to be treated or beneficiated to meet commercial specification (Refaei *et al*., 2017). Kaolin has inherent impurities such as quartz and mica that limits its applications (Virta, 2012; Salahudeen *et al*., 2015). These impurities can be removed via. air cyclone. Abubakar *et al*. (2012) reported the use of air cyclone as classification equipment, hence, cyclone may be used to classify purified kaolin. The physical and chemical properties of kaolin dictate its utilization in processing industries and therefore beneficiation is required before usage (Ombaka, 2016). There is large deposit of kaolin clay around the world and Nigeria has about two billion metric tons scattered all over the country (Salau and Osemeke, 2015). Kaolin requires purification to enhance the applicability in catalyst synthesis such as zeolite where high degree of purity is required. The removal of quartz and mica impurities in kaolin based on single stage air cyclone has been reported in many literatures to have low yield thereby making it uneconomical. The uneconomical low yield has necessitated research efforts for higher yield by application of multiple stage cyclone systems. Consequently, this research presents the design, construction and performance evaluation of a parallel cyclone system for kaolin clay beneficiation to improve the yield over a single cyclone system.

MATERIALS AND METHODS

Raw kaolin clay was obtained from Kankara Local Government area of Katsina State-Nigeria. The designed and fabricated air cyclone rig included an air blower with motor of 1HP, U-tube manometer, 3 stage cyclones each of 0.1 m in diameter. The design of the parallel air cyclone system was carried out using Eq. 1-3. The design equations were used theoretically to obtain some input parameters such as inlet velocity, cyclone diameter and particle cut size diameter. CAPED Software was used to design the air cyclone and the parameters used in the design are presented in Table 1. Figure 1 presents a view of the designed air cyclone in the CAPED Software:

$$d_{pc} = \sqrt{\frac{9\mu}{\pi N_i V_i(\rho_p - \rho_f)}} \quad (1)$$

But:

$$\left(d_{pc}\right)^2 = \frac{9\mu b}{\pi N_i V_i\left(\rho_p - \rho_f\right)} \quad (2)$$

$$N_e = \frac{1}{a}\left[L_b + \frac{L_c}{2}\right] = \frac{1}{a}\left[L_b + \frac{L\text{-}h}{2}\right] \quad (3)$$

For high efficiency air cyclone (Sinnott, 2005):

$$\frac{a}{D_c} = 0.5, \frac{b}{D_c} = 0.5, \frac{D_e}{D_c} = 0.5, \frac{h}{D_c} = 1.5,$$
$$\frac{H}{D_c} = 2.5, \frac{S}{D_c} = 0.375$$

Where $h = L_b = 1.5D_c, H = 2.5D_c, a = 0.5D_c$, from Eq. 3:

$$N_e = \frac{1}{a}\left[L_b + \frac{L_c}{2}\right] = \frac{2.75}{0.5} = 6 \text{ turns}$$

Similarly:

$$\left(D_{pc}\right)^2 = \frac{9\mu b}{\pi N_i V_i(\rho_p - \rho_f)}$$

Table 1: Definitions of the parameters used in the design equations

Terms	Definitions
D_e	Overflow outlet diameter
a	Cyclone inlet height
b	Cyclone inlet width
$h = S = L_b$	Cyclone cylindrical height
$Z_c = L_c$	Cyclone conic length
p	Particle density
f	Fluid density
μ	Fluid viscosity
L = H	Total length
dpc	Particle cut size diameter
D_c	Cyclone body diameter
Vi	Cyclone inlet velocity
$N_i = N_e$	Number of turns
B	Underflow outlet diameter

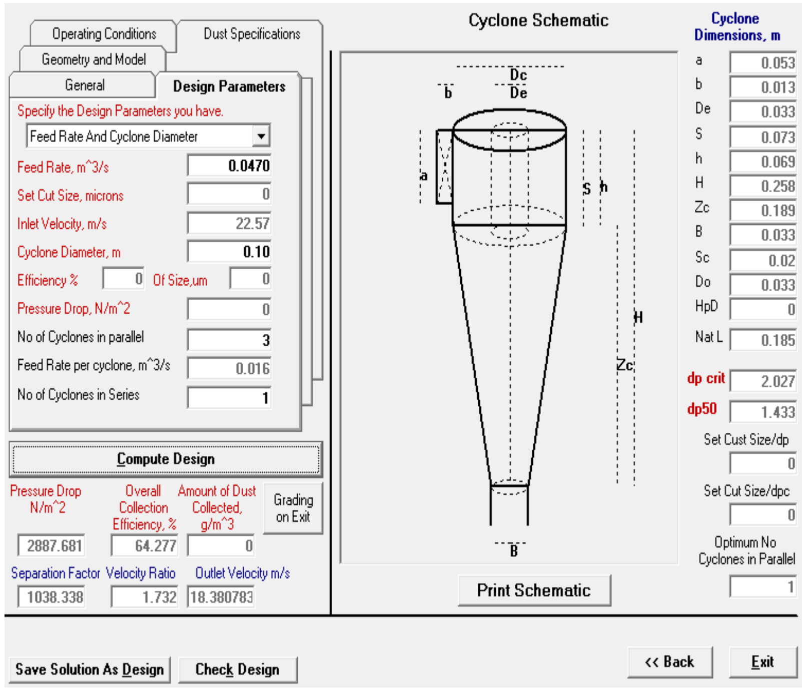

Fig. 1: The design interface showing the specification of the cyclones

$$b = 0.2D_c,\ \rho_p\text{-}\rho_f = 2610\text{-}1.0819 = 3608.91,$$
$$V_i = 15\,\text{m}\,\text{sec}^{-1},\ N_i = 6$$

Where the air viscosity, $\mu = 1.953\times10^{-5}$.

RESULTS AND DISCUSSION

The input parameters were obtained from the theoretical knowledge of the design equations while the output parameters which were used during the fabrication of the rig were obtained from the CAPED Software design interface shown in Fig. 1. It shows the specification of the cyclone while Fig. 2 shows the fabricated cyclone rig showing the hopper, distribution chamber, the three cyclones and overflow collectors case. The overflow collectors were enclosed in one unit which was used to beneficiate Kankara kaolin clay. Table 2 presents the material balance across the cyclone using a basis of 1 kg of raw Kankara kaolin clay. Table 3, the values of pressure drop across the cyclones are presented. Table 4 presents the Particle Size Distribution (PSD) results for the samples feed into the cyclone. Figure 3 presents the XRD pattern of the feed and products overflow of first, second and third cyclone depicted as PO1, PO2 and PO3, respectively.

Table 2 presents the total percentage yield of 30.18% and the percentage loss of 2.11% after 1.0 kg was run through the three cyclones in parallel. Audu *et al*. reported an average yield of a single system cyclone as 15% whereas the total yield obtained in this work is an improvement over the yield obtained in a single cyclone system. The first cyclone yield of 19% also surpassed the yield in the single cyclone system. The losses recorded were along the processing route and the resistances along the flow channel. It was discovered that the feed into the cyclone were not evenly distributed due to the positioning of the pipes connected to individual cyclone. It was also discovered that after the test run, about 46.3% of the feed went through the first cyclone, 21.1% through the second cyclone and 30.5% through the third cyclone, hence the yield from the first cyclone is expected to be the highest.

Table 3 presents the pressure drop across the 3 cyclone. The range of pressure drop in this parallel arrangement was supposed to be averagely the same if the flow to the 3 cyclones in parallel was evenly distributed. However, this was not so due to the inability to achieve a uniform velocity for the 3 cyclones. Additionally, there was no position in the distribution chamber where the 3 pipes leading to the three cyclones would have equal flow rate and this was the reason why there were slight differences in their pressure drops. Hence, the pressure drop range in this parallel arrangement conformed to literature and the efficiency of the air cyclone will not be much affected due to the short range of the pressure drop. Furthermore, the particle size distribution for clay material are generally classified as: clay (1-2 μm), silt (2-63 μm) and sand (63-2500 μm). As presented in

Fig. 2: A view of the designed and constructed parallel air cyclone rig for kaolin beneficiation

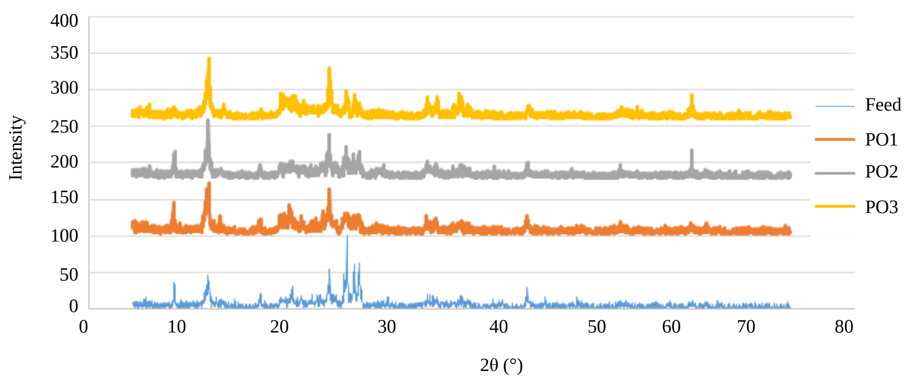

Fig. 3: XRD pattern of the feed and products overflow of first, second and third cyclone depicted as PO1, PO2 and PO3, respectively

Table 2: Material balance across the test rig on the basis of 1 kg of feed

Cyclones in Parallel	Kaolin feed (kg)	Amount of over-flow product (kg)	Amount of under-flow product (kg)	Percentage yield (wt. %)	Percentage losses (wt. %)
First cyclone	-	0.1902	0.2731	-	-
Second cyclone	-	0.0512	0.1595	-	-
Third cyclone	-	0.0604	0.2445	-	-
Total	1.0	0.3018	0.6771	30.18	2.11

Table 3: Pressure drop across the cyclones

Different stages in parallel	Initial reading (h_1) (m)	Final reading (h_2) (m)	Difference in h Δh (m)	Cyclone Eff. %	Pressure drop across the cyclone (Pa)
First cyclone	0.222	0.140	0.082	55	820
Second cyclone	0.218	0.150	0.068	55	680
Third cyclone	0.214	0.140	0.074	55	740

Table 4: Description of the PSD of kaolin feed and products obtained from the test rig

Samples	Description	Clay (%) (1-2 μm)	Silt (%) (3-63 μm)
Feed	Whitish fine grain powder	46	54
PO1	Whitish fine grain powder	60	40
PO2	Whitish fine grain powder	70	30
PO3	Whitish fine grain powder	64	36
PU1	Whitish fine grain powder	45	55
PU2	Whitish fine grain powder	42	58
PU3	Whitish fine grain powder	42	58

Table 4, the particle size distribution analysis of the kaolin feed was 46% kaolin clay and 54% impurities (silt). The overflow products for the first, second and third cyclones gave powder classification of 60, 70 and 64% particles ≤2 μm, respectively. This shows a great improvement over the feed which has initial percentage clay of 46%. It was also observed that the highest purification was obtained at the second cyclone with 70% kaolin clay content. This could be attributed to the stream of the second cyclone being directly from the top of the distribution chamber resulting to the finest particles passing through that stream. The second cyclone which had clay content of 4% higher than the first cyclone may be attributed to the amount of the feed and the cyclone inlet velocity. If the feed rate is low and inlet velocity is low it is therefore expected that product purity be high at a low yield.

The X-Ray diffraction analysis presented in Fig. 3. A feed of very strong peaks at Bragg's 2O angle of 12.35, 24.88 and 26.65° and strong peaks at 8.8, 17.4 and 45.24° respectively. The kaolinite characteristic peaks in the XRD patterns are usually 2O diffraction angles of 12.35, 24.88 and 45.24°. It was observed that the peaks at Bragg's angles of 12.35, 24.88, 20.38 and 45.24° responsible for the kaolinite mineral were more prominent after beneficiation as shown in product samples PO1, PO2 and PO3. It was also observed that the peak at 26.65° responsible for quartz was drastically suppressed as shown in product sample PO1, PO2 and PO3. Generally, the level of beneficiation obtained at the PO1, PO2 and PO3 improved the raw kaolin by 66.2, 69.5 and 67.7% respectively. These were obtained using the average increment in the intensities of the characteristic peaks of kaolinite. This shows an average beneficiation for cyclone as 67.8%. The quartz in the feed at PO1, PO2 and PO3 was drastically reduced by an average of 95, 82 and 82%, respectively with an average percentage reduction of86.3%. Similarly, the mica in the feed was reduced at the PO1, PO2 and PO3 by 50, 60 and 60% respectively with an average percentage reduction of 56.7%.

CONCLUSION

An air cyclone arranged in parallel beneficiation rig was successfully designed using CAPED Software and fabricated to a capacity of 182 kg h^{-1} to beneficiate Kankara kaolin. The feed and the products of purification obtained from the rig were analyzed. The yield obtained from the rig was 30.18% which was an improvement over previous reported average yield of 15% for a single stage cyclone system. The PSD showed that the clay content was improved from 46 to an average 65%. The XRD analysis also showed that the level of beneficiation obtained at the cyclone had improve the kaolinite content in the raw kaolin by an average of 67.8%, the quartz in the feed was reduced by an average of 86.3% while the mica in the feed was reduced by an average of 56.7%.

RECOMMENDATIONS

However, further investigations should be carried out on the design and fabrication of air cyclone for kaolin beneficiation recycling plant to compare the cost, quality and quantity of the yield with the results obtained in this study. This could help to determine a better and economically viable process of kaolin beneficiation.

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